Understanding Hadronic Mass
Through Light Meson Structure at the EIC

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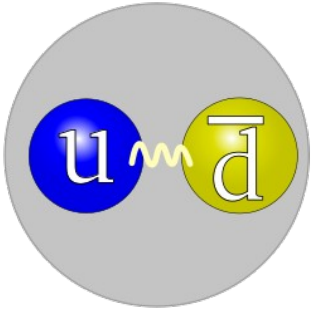
University of Regina

Outline

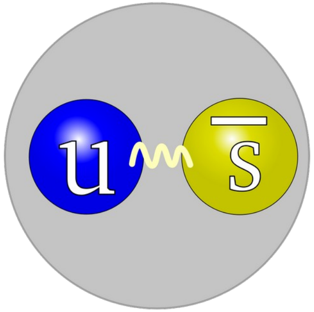
- Understanding hadronic mass generation
  - Form Factor Measurements
- Form Factor Measurements at the EIC
- Introduction to Event Generator – DEMPGen
- Generator updates
- Summary

Understanding hadronic mass generation

- Understanding the origin of the masses of protons and neutrons as >99% of the visible mass of the universe resides in atomic nuclei.
- The Higgs mechanism, through which fundamental particles acquire mass, can explain only a small fraction of the nucleon mass (~1%).
- The majority of the mass comes from the strong interactions that bind the quarks and gluons together.
- We do not adequately understand the mass generation mechanisms of the strong interaction.
- To address the emergence of hadronic mass can examine the lightest mesons, the pion and kaon.



Pion (π^+)

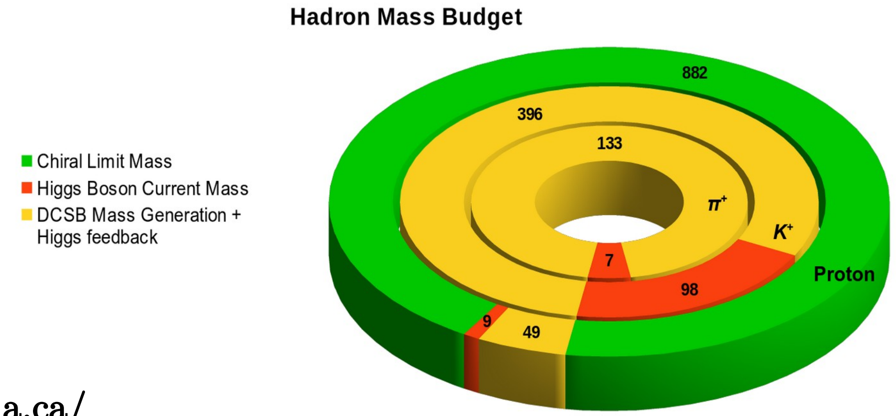


Kaon (K^+)

http://lichen.phys.uregina.ca/

Meson Form Factors

- Higgs mechanism has more influence on the kaon mass than the pion due to the presence of a heavier strange quark (~101 MeV).
- Hadronic mass generation is directly linked to the internal structure of the constituents.
  - Can examine this internal structure by looking at quantities like the form factor.
  - Form factor describes the spatial distribution of partons within a hadron.
- Charged pion ($\pi^{\pm}$) and kaon ($K^{\pm}$) form factor comparison (F_{π} , F_K) would provide unique information about hadronic mass generation.



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Form Factor measurements

- One of the ways to measure the form factor is through Deep Exclusive Meson Production (DEMP) reactions.

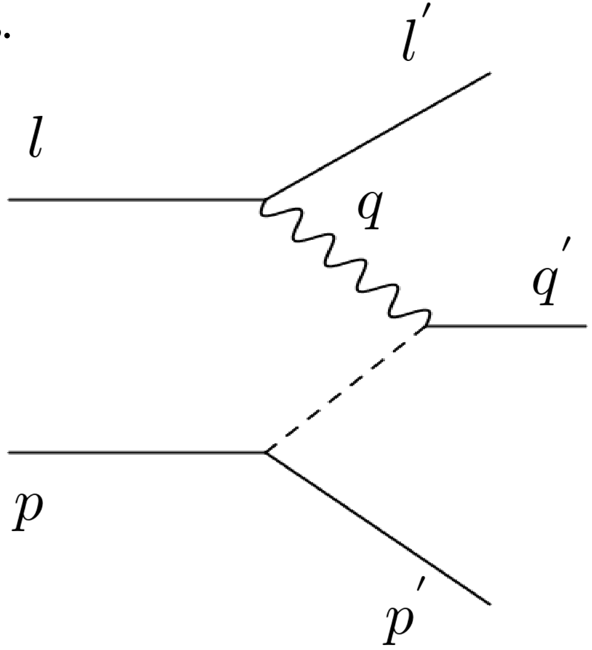
$$e^- + p \rightarrow e^{-'} + K^+ + \Lambda^0/\Sigma^0$$
$$\downarrow \quad \downarrow \quad \downarrow \quad \downarrow \quad \downarrow$$
$$l + p \rightarrow l' + q' + p'$$

- Indirectly use the “kaon cloud” of the proton via the p(e,e' $K^+\Lambda^0/\Sigma^0$) process.
- Basic Kinematic invariants are
  - γ^*p squared CM energy

    $$W^2 = (q+p)^2$$
  - Photon virtuality

    $$Q^2 = -q^2 = (l - l')^2$$
  - Squared 4-momentum transfer to the nucleon

    $$t = (p - p')^2 = (q - q')^2$$



Total Cross-section Calculations

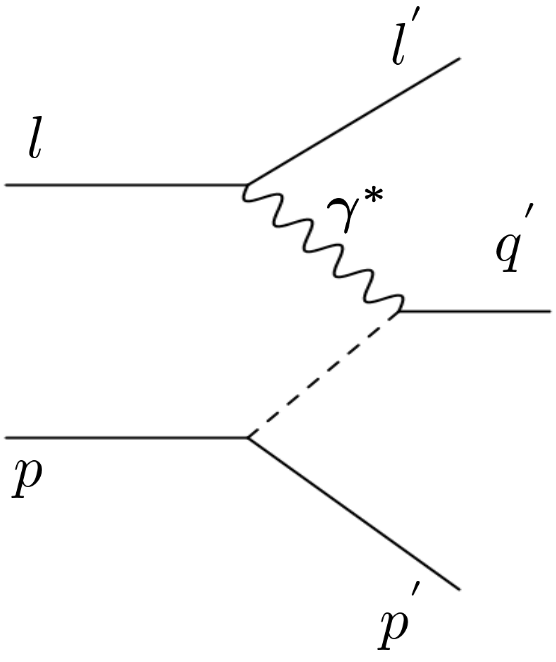
- We will consider the one-photon-exchange approximation.
- We can define total cross-section as

$$\sigma = \sigma_T + \epsilon\sigma_L$$

  - Extract σ_T and σ_L based on the polarization of a virtual photon.
  - σ_T corresponds to the transverse component of the virtual photon.
  - σ_L corresponds to the longitudinal component of the virtual photon.
  - ϵ is the photon polarization parameter.

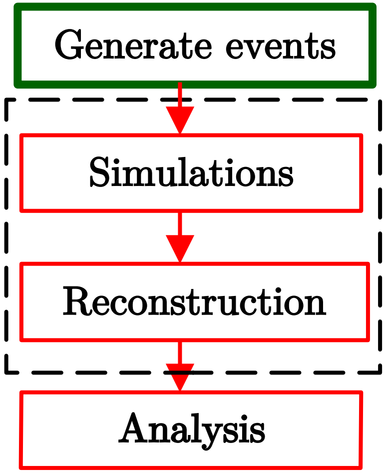
$$\epsilon = \frac{2(1-y)}{1+(1-y)^2}$$

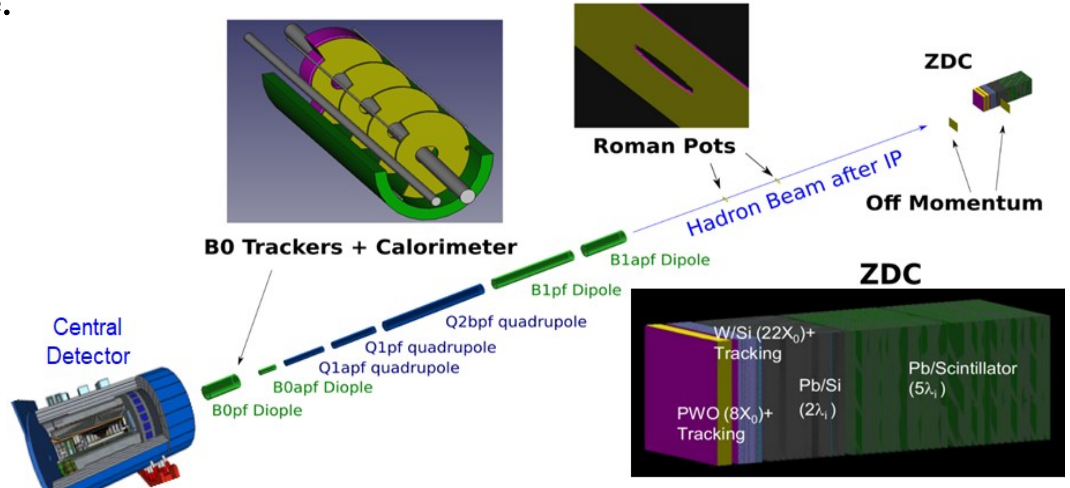
Where the fractional energy loss, $y = \frac{Q^2}{x(s_{tot}-M_N^2)}$



Form Factor measurements at the EIC

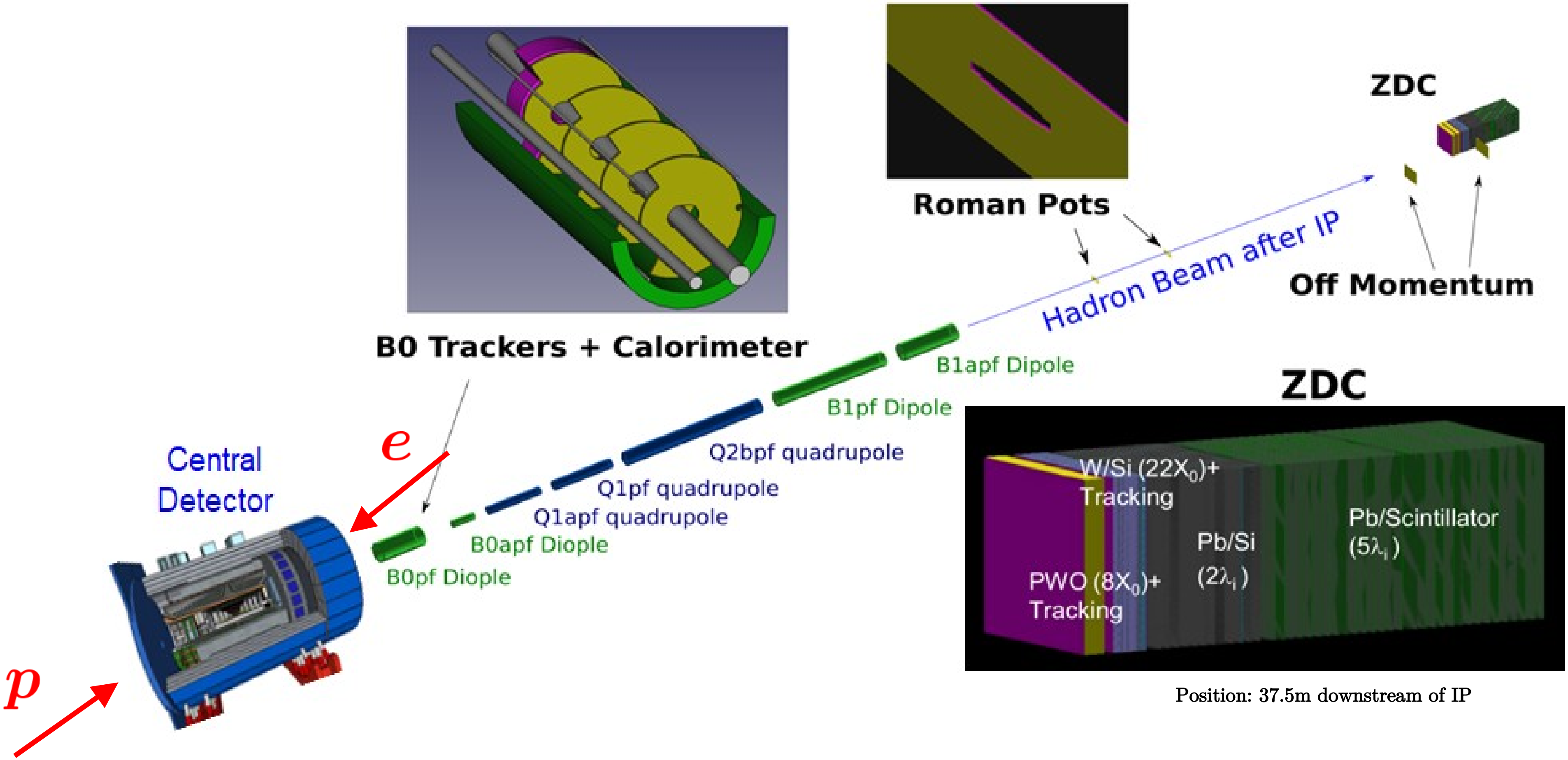
- Challenging to measure exclusive reactions of interest.
  - Triple coincidence.
  - One of those particles will further decay and make the detection more complicated.
- Need to test if the triple coincidence measurement is possible!
- To test this, run simulations.
- The first step will be to generate an event sample.





Position: 37.5m downstream of IP

Exclusive reaction



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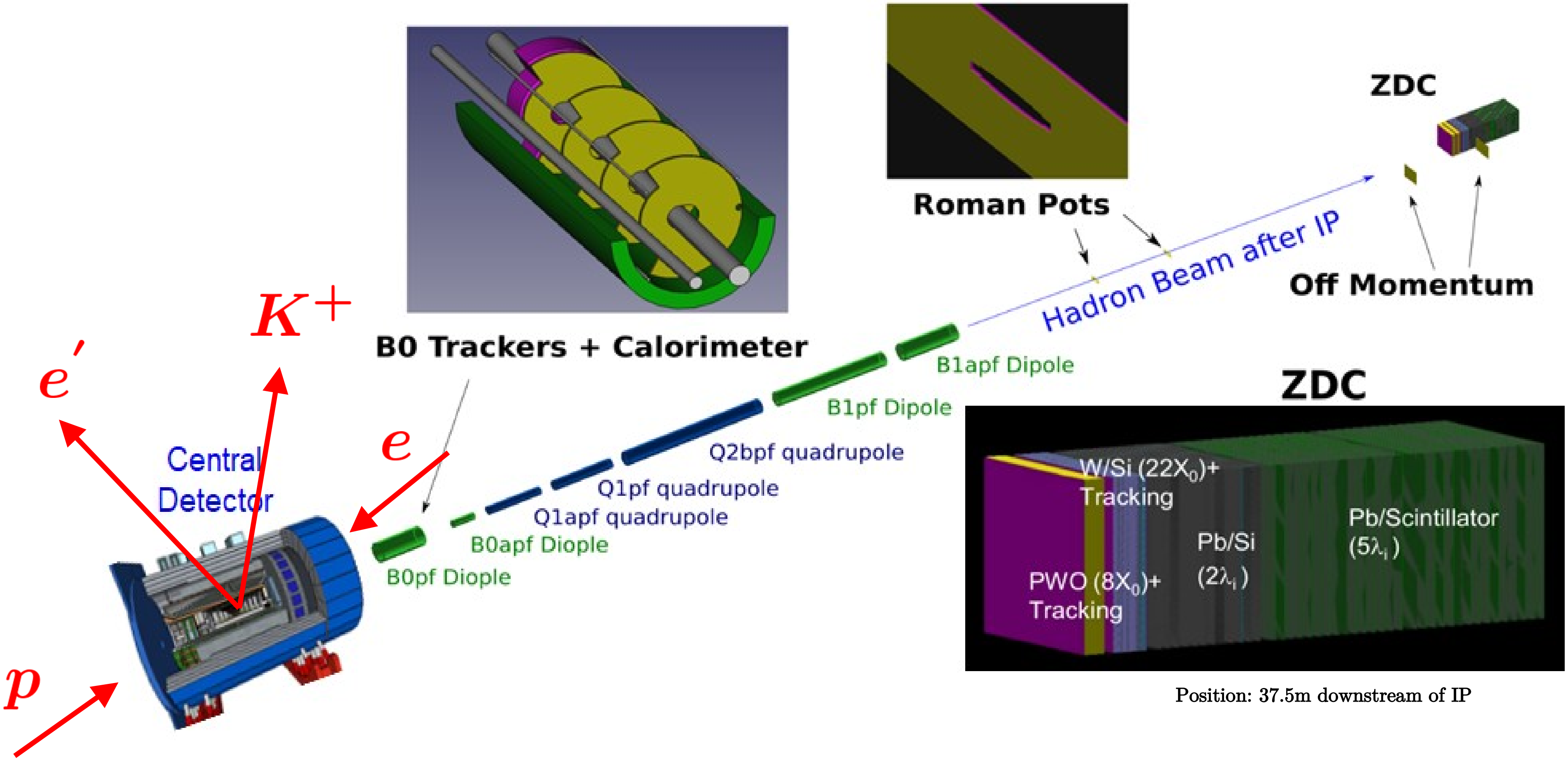

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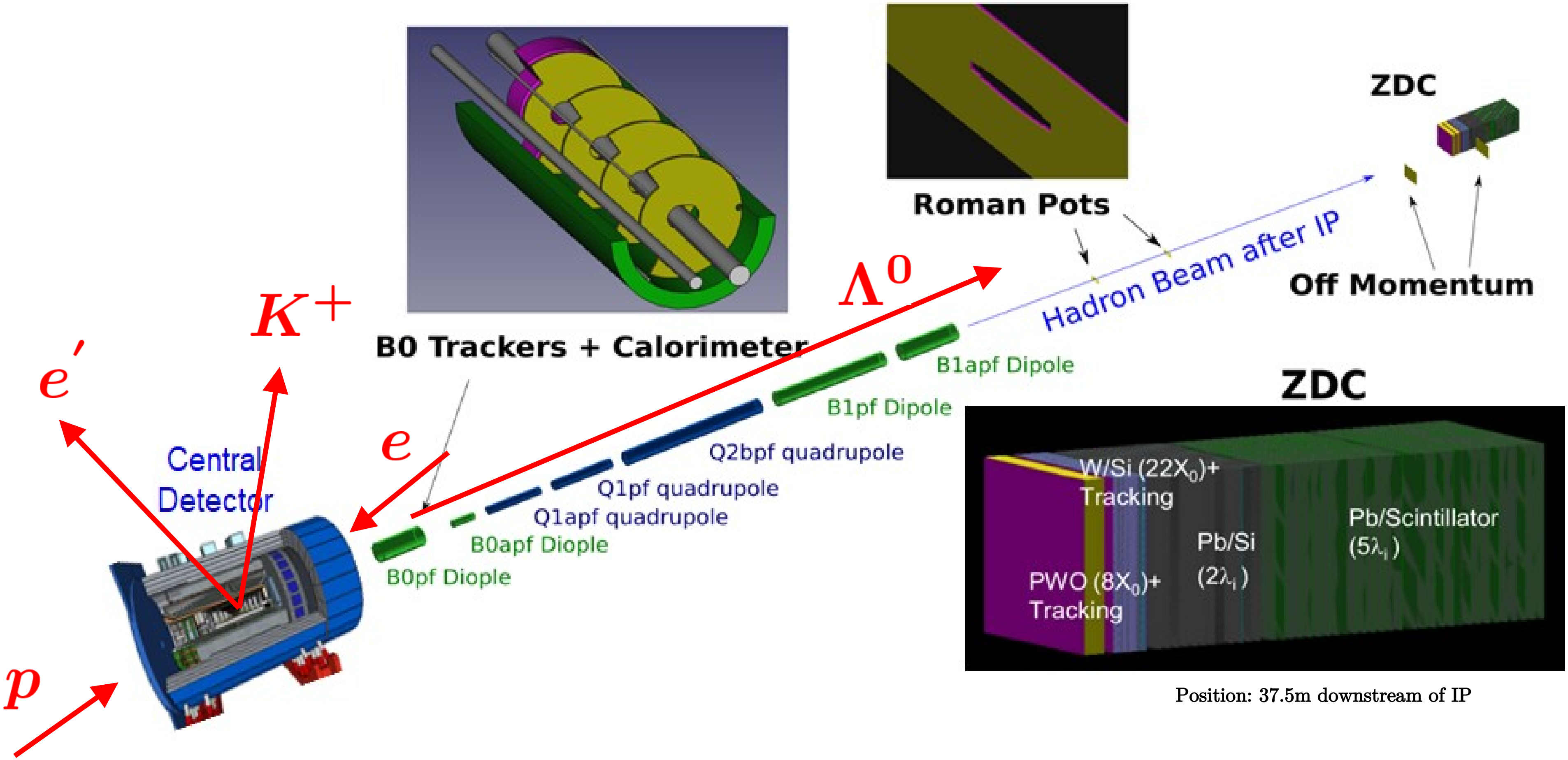

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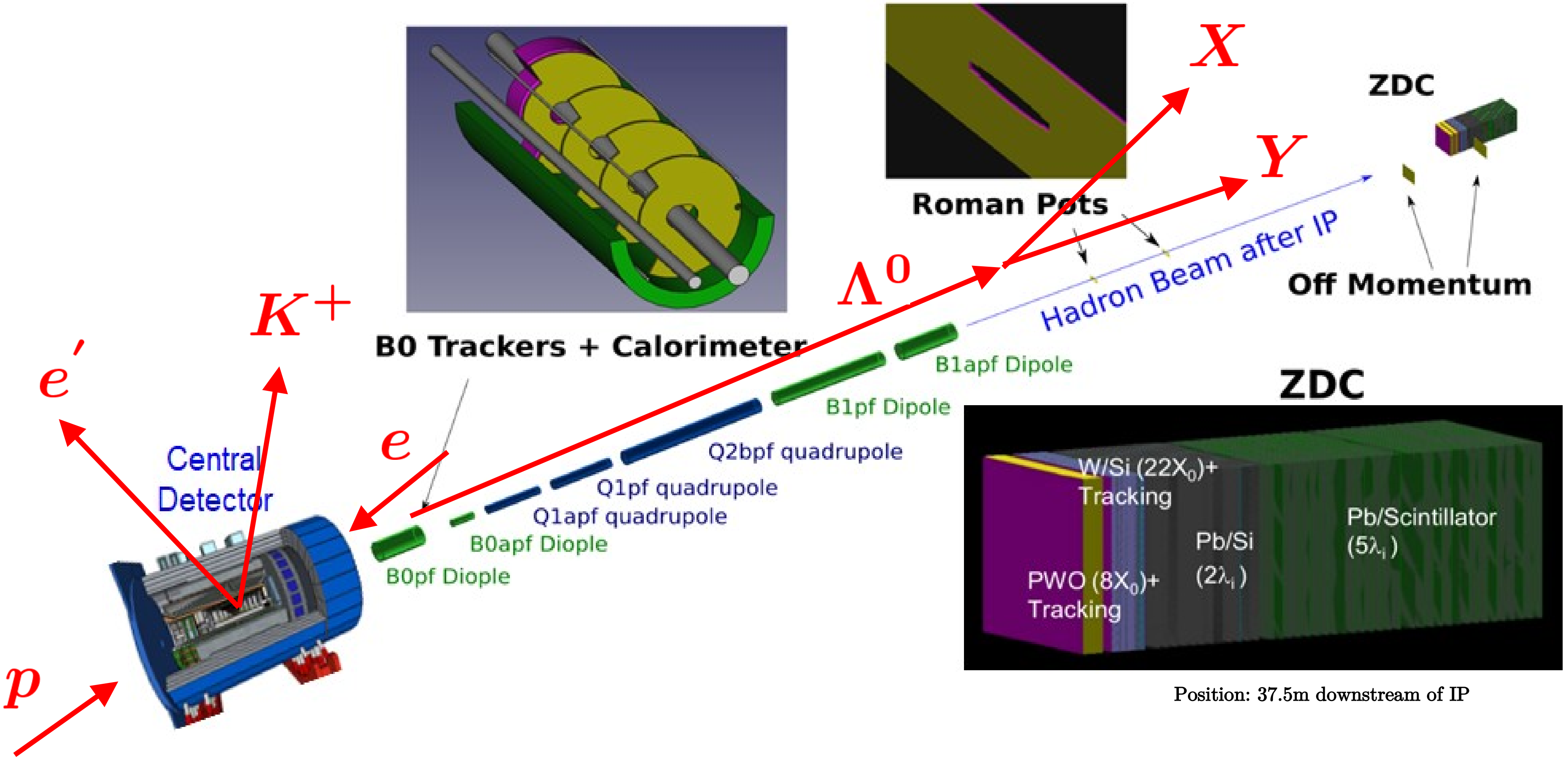
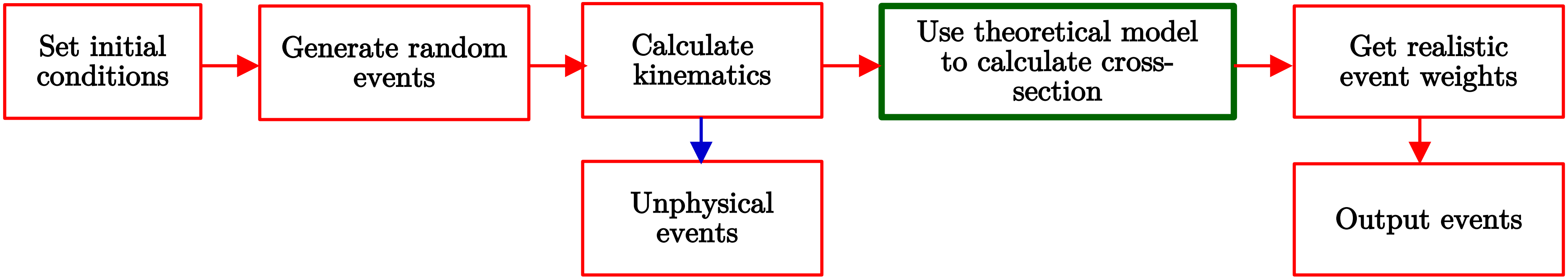


Position: 37.5m downstream of IP

Introduction to DEMPGen

- Generating the events using a bespoke DEMP event generator.
- How does the generator work?

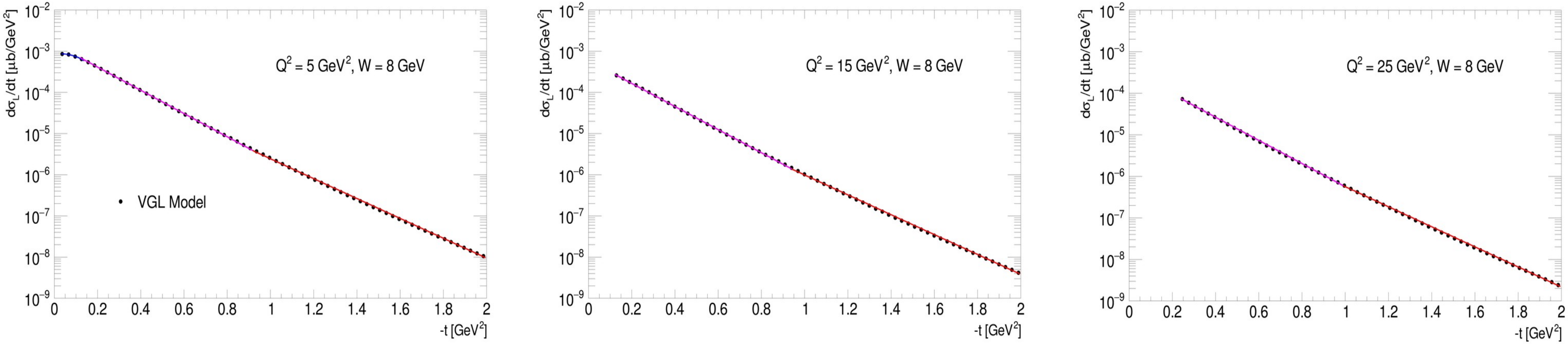


- We already have an existing pion module in the generator for the EIC.
- Trying to upgrade the pion module.
- Implementing a new kaon module into the generator.

https://github.com/JeffersonLab/DEMPGen.

Generator Updates for Λ^0 Channel

- Two channels for the kaon module
- Begin with $p(e,e' K^+\Lambda^0)$ reaction.
- Use the Regge-based $p(e,e' K^+\Lambda^0)$ model from M. Vanderhaeghen, M. Guidal and J.-M. Laget (VGL).
  - MC event generator created by parametrizing VGL σ_L, σ_T for $1<Q^2<35$, $2<W<10$, $0<-t<2$.
    - Parametrize in step sizes of 1 GeV in W and 1 GeV^2 in Q^2.
  - Parametrize σ_L with a polynomial, exponential and exponential.



VGL Model - M. Guidal, J.-M. Laget, M. Vanderhaeghen, PRC 61 (2000) 025204.

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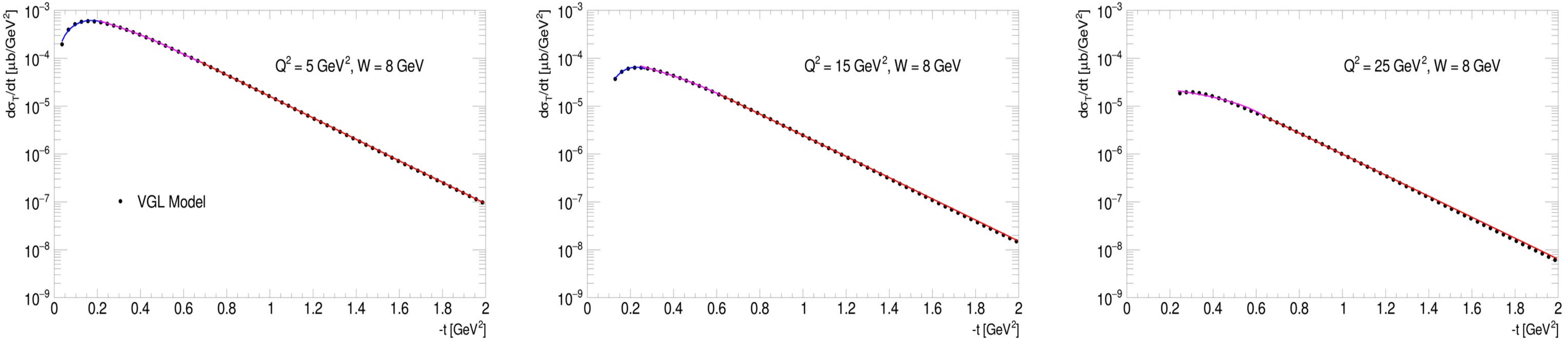

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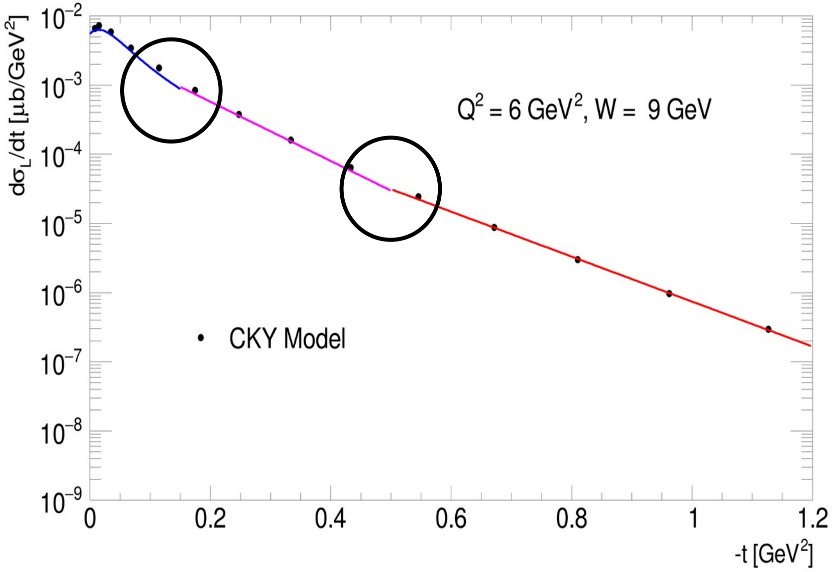
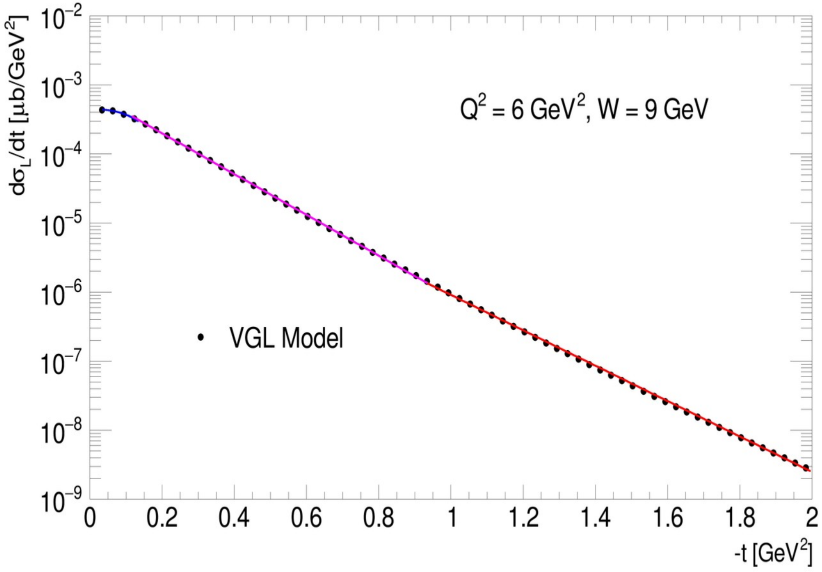
DEMPGen Improvements

- In the pion module, there were discontinuities between the different parametrization functions.
  - For kaon module, removed by finding the intersection points between the functions.

$\sigma_L\ (\pi^+)$



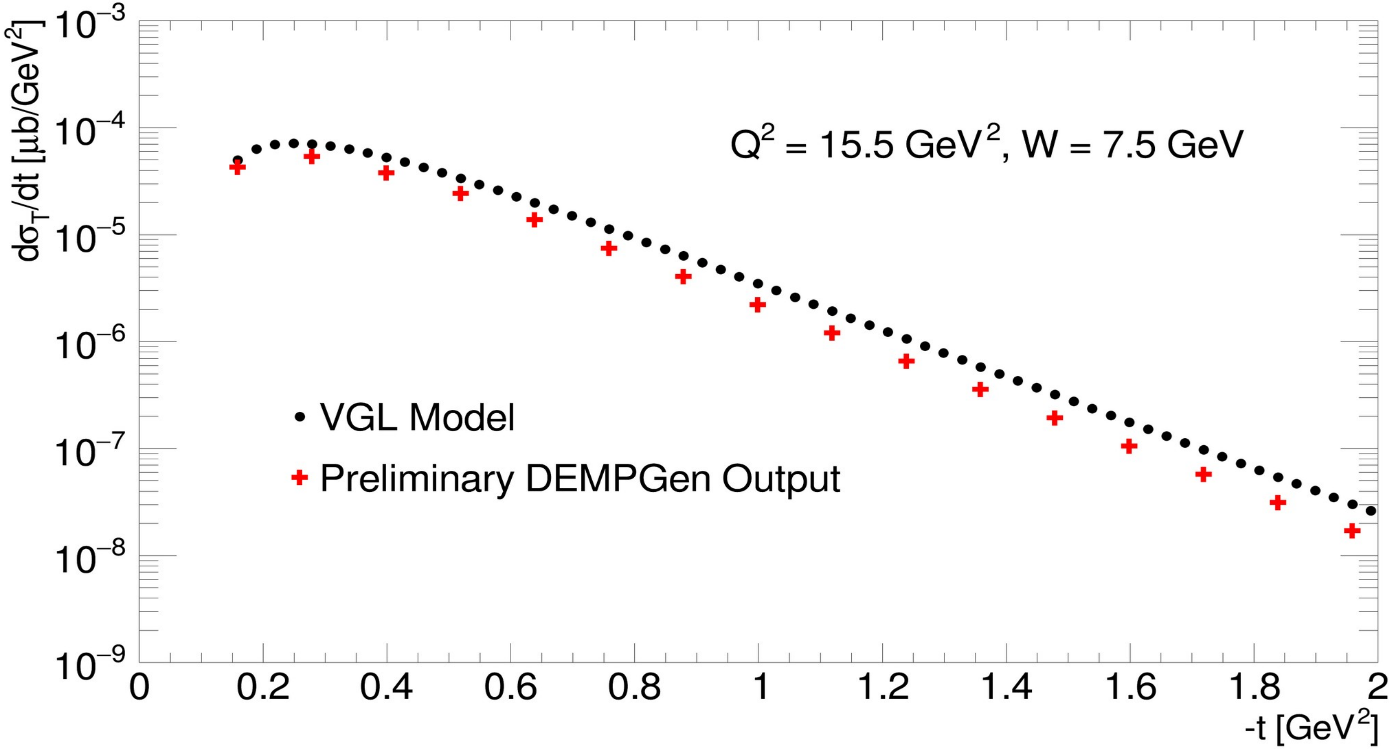
$\sigma_L\ (K^+)$



T. K. Choi, K. J. Kong and B. G. Yu, Journal of the Korean Physical Society 67, 1089 (2015).

DEMPGen Improvements

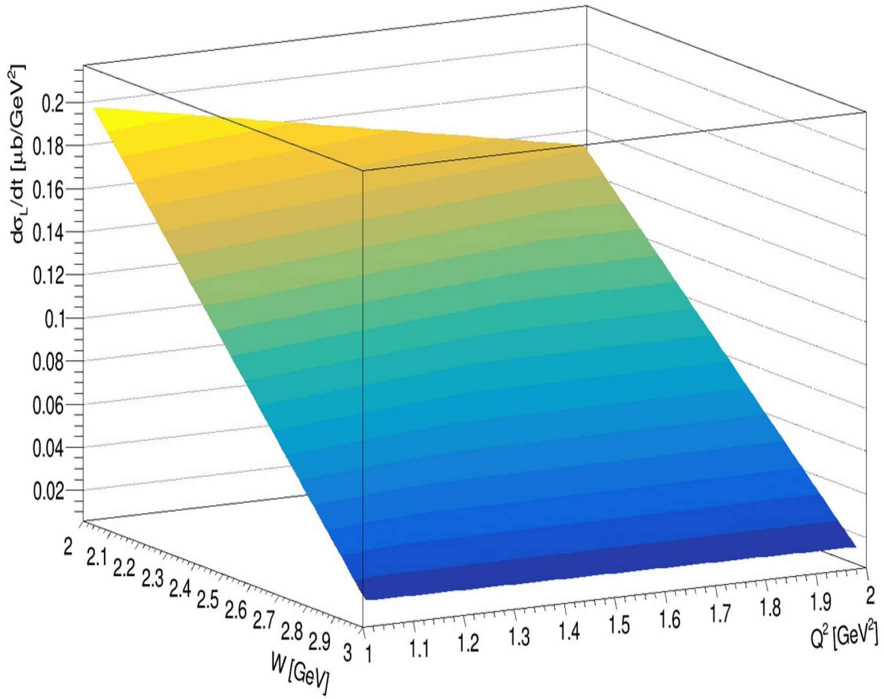
- Because of the finite step size in W and Q^2, points far from the parametrization differ from the model.
  - Implemented a new method to interpolate the parametrization.

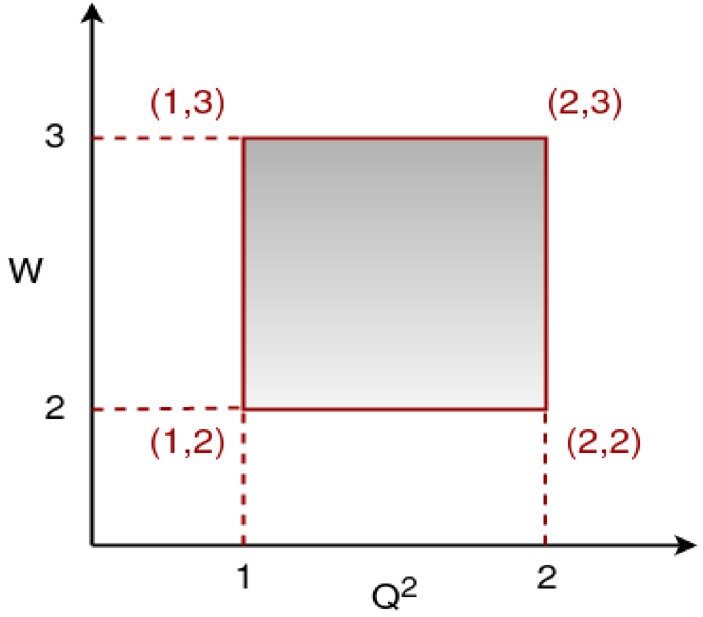


Interpolation Method

- How does the interpolation work?

$$f(x,y) = f(a,b) + f_x(a,b)(x-a) + f_y(a,b)(y-b)$$





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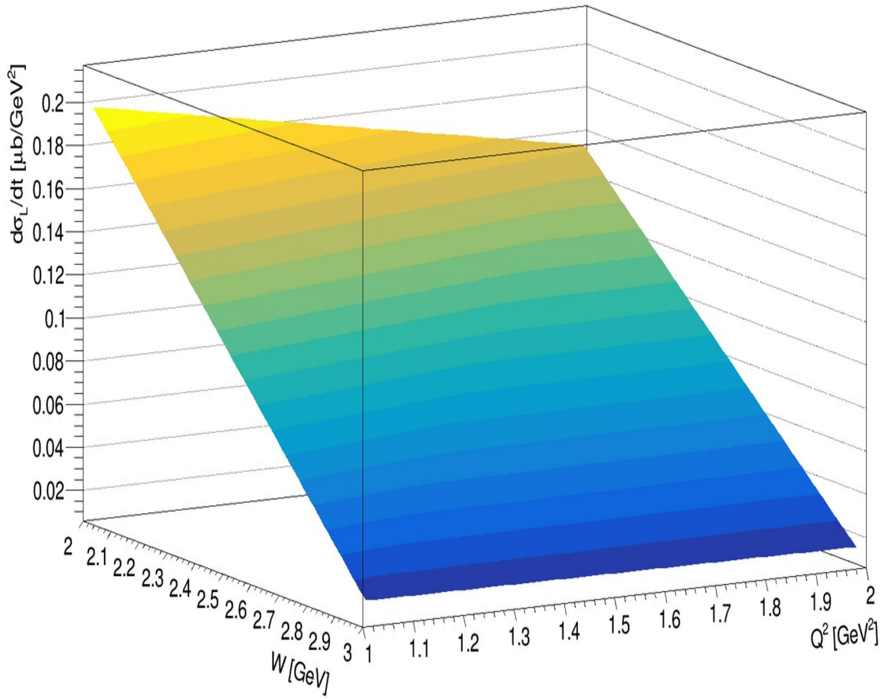
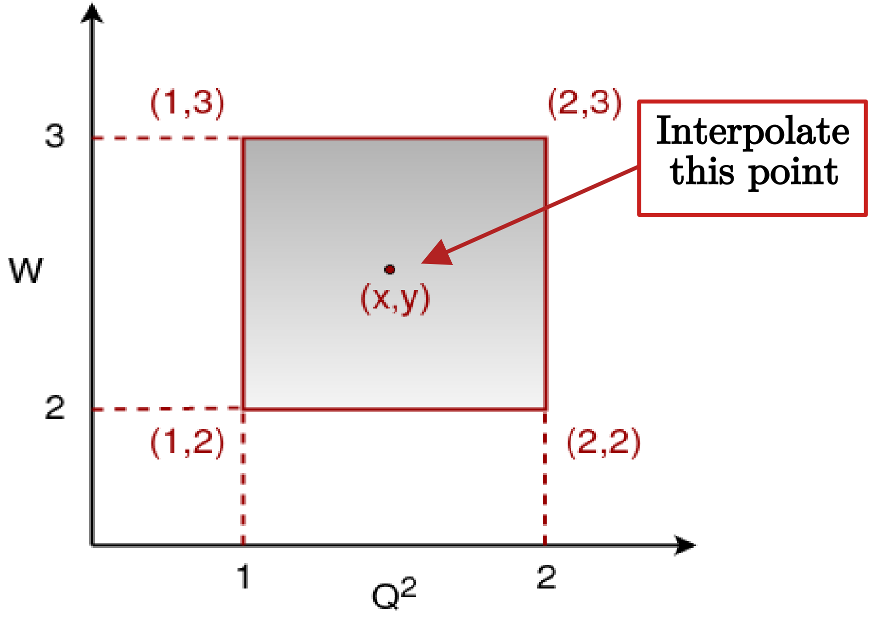
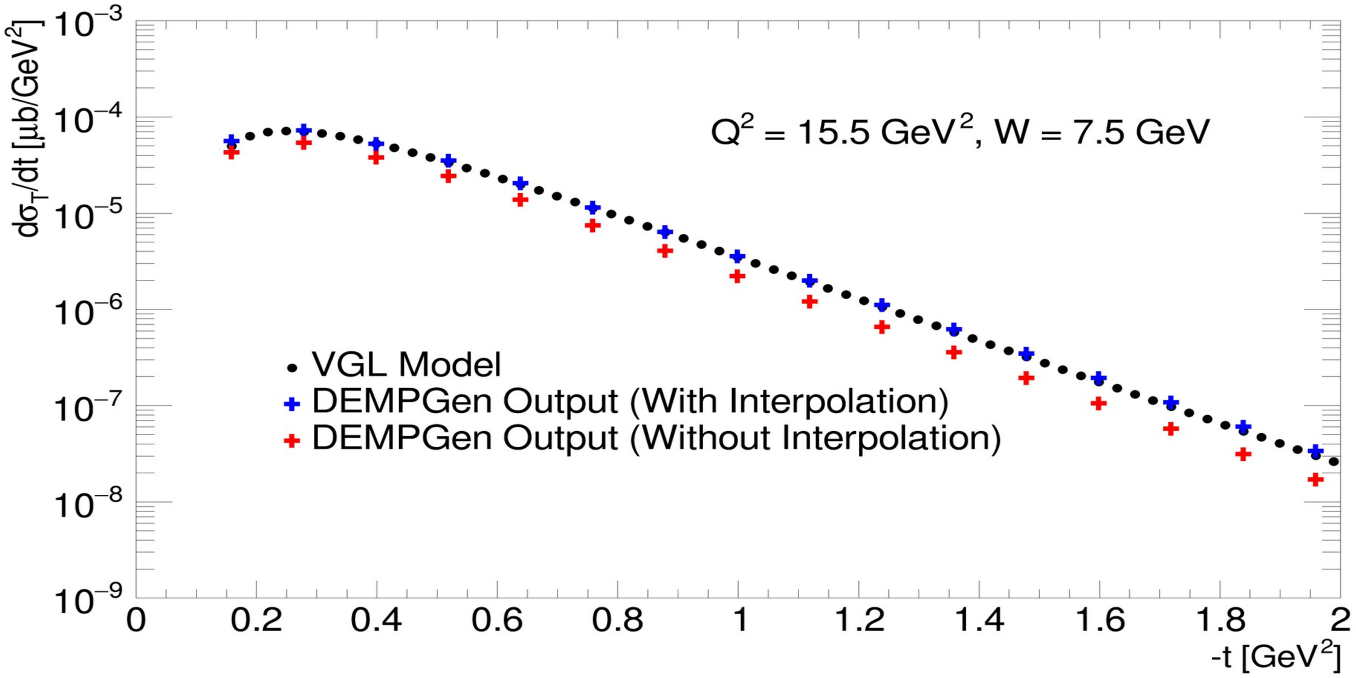




DEMPGen Improvements

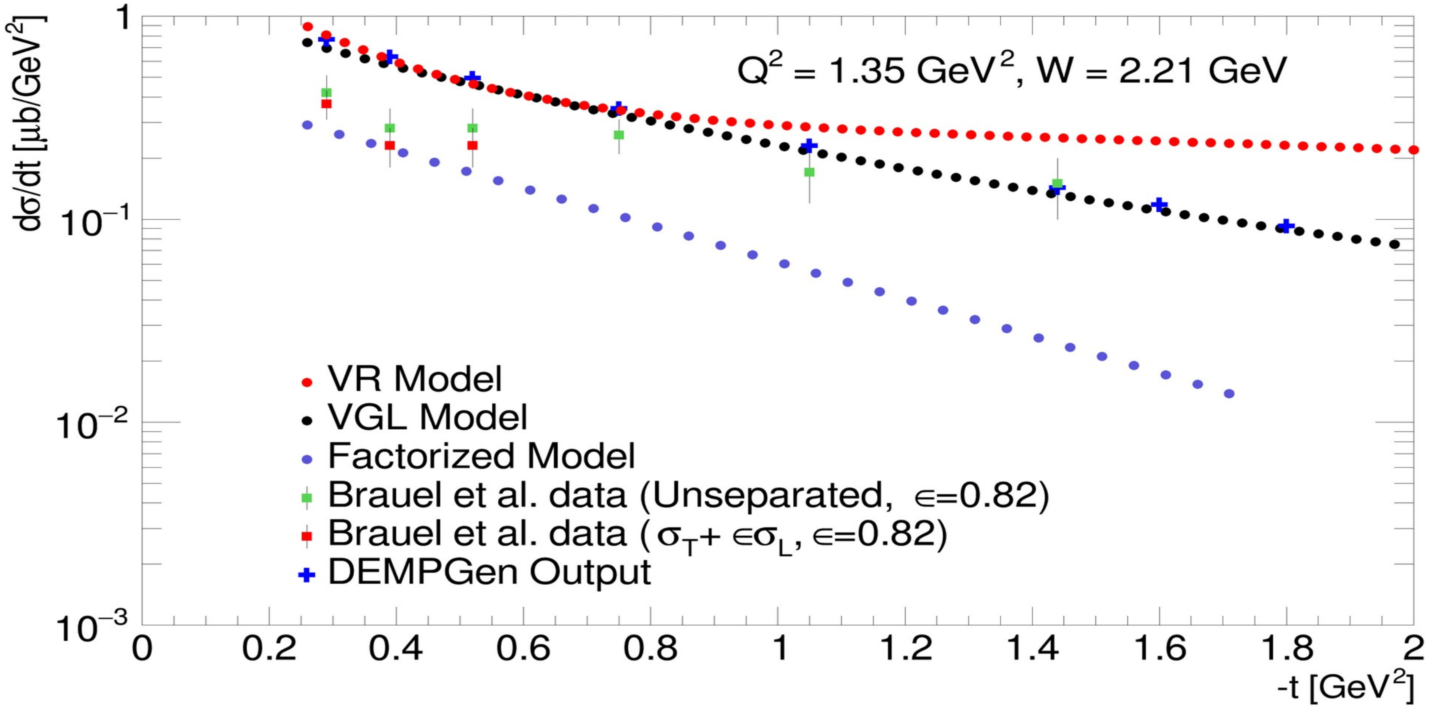
- Interpolating yields values much closer to the output of the model.
- For now, interpolation only in the kaon module.
  - Will include this in the pion module soon.



Cross-section Plot for Λ^0 Channel

- For the $p(e,e' K^+\Lambda^0)$ channel, very limited data, only at $Q^2 = 1.35$ GeV^2 and W = 2.21 GeV.

$$\sigma = \sigma_T + \epsilon\sigma_L$$



T.Vrancx, J. Ryckebusch, PRC 89(2014)025203

Factorized Model PRC 85, 018202 (2012)

Generator Updates for Σ^0 Channel

- For the p(e,e' $K^+\Sigma^0$) module, the generator uses the Regge-based p(e,e' $K^+\Sigma^0$) model M. Vanderhaeghen, M. Guidal and J.-M. Laget (VGL) in a similar way to the lambda channel.
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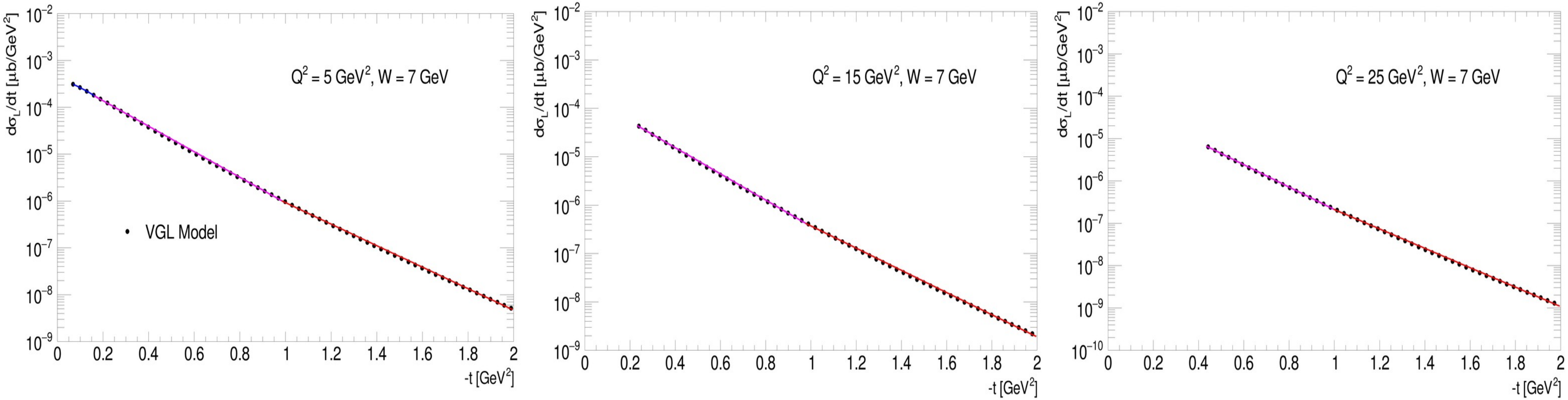

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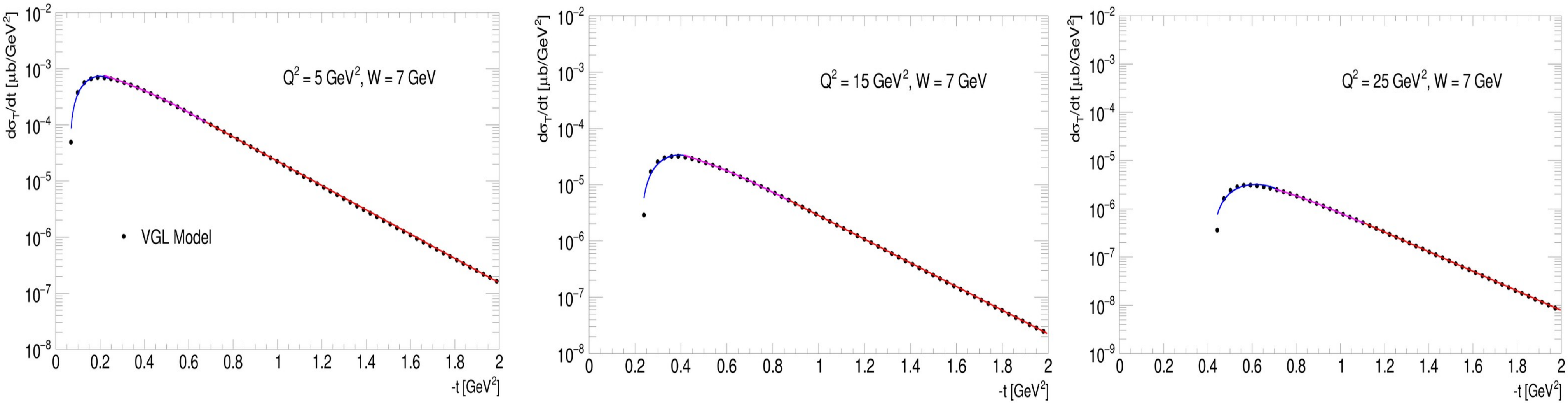

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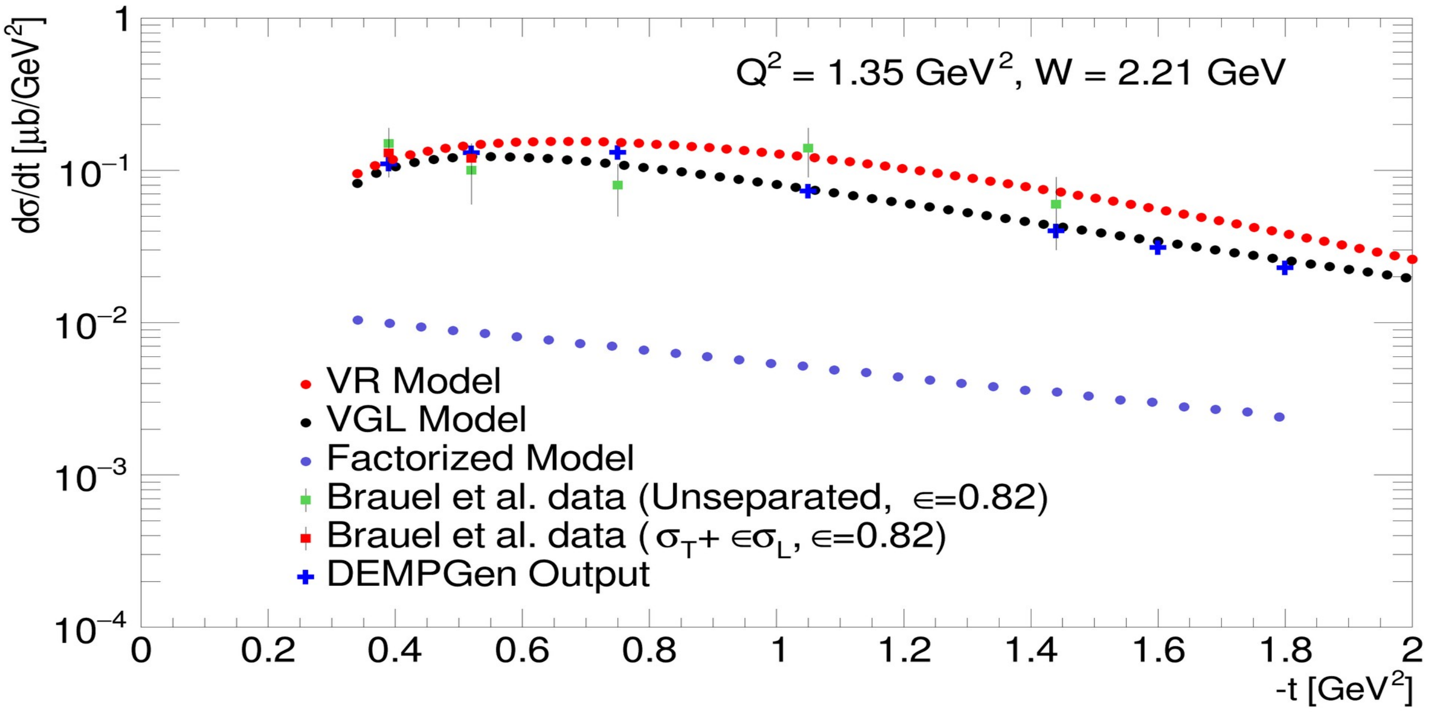
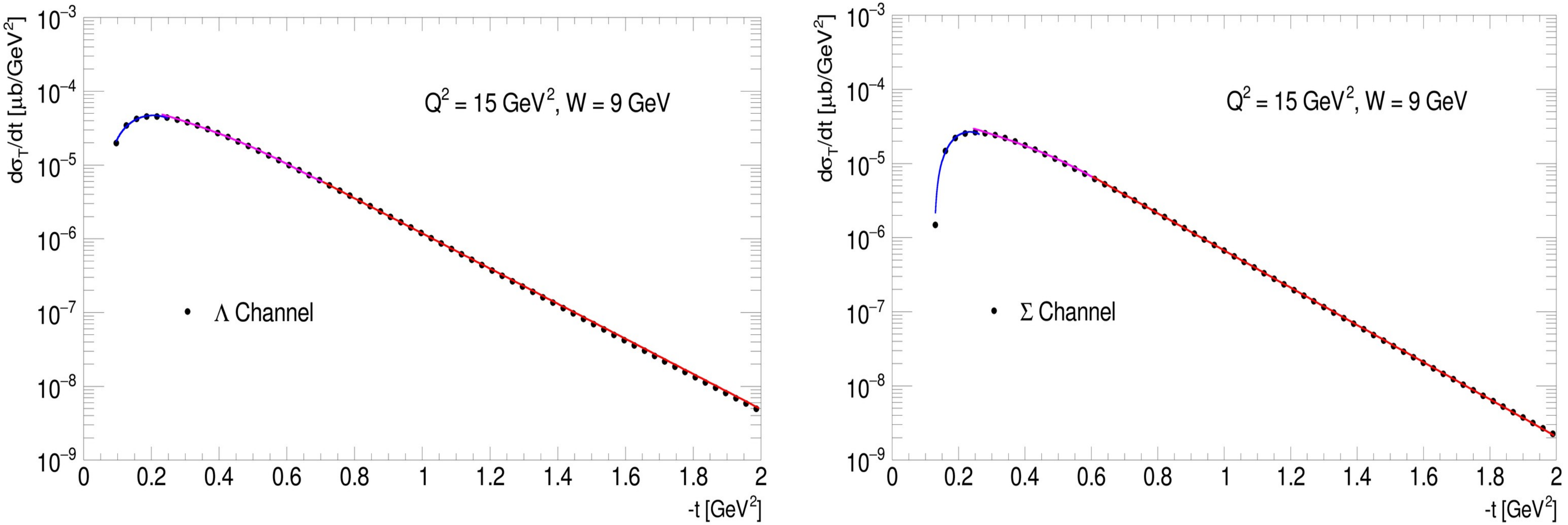


Comparison of Λ^0 and Σ^0 Channels

- The main difference arises while calculating σ_T for each channel.
- σ_L behaves similarly for each channel.



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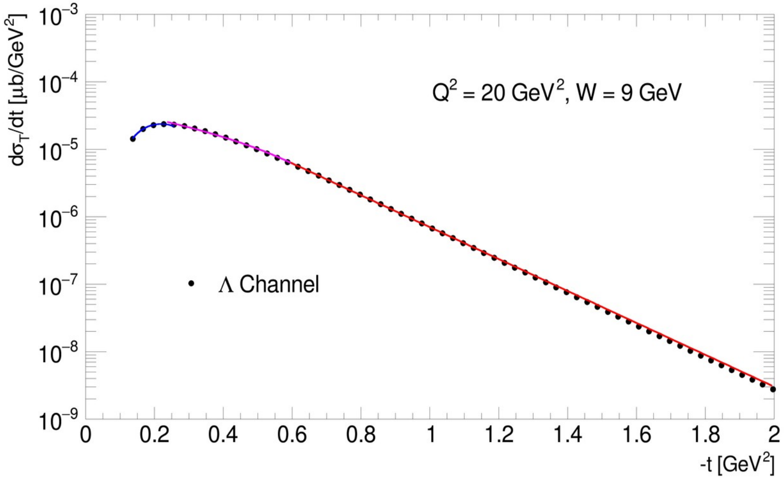

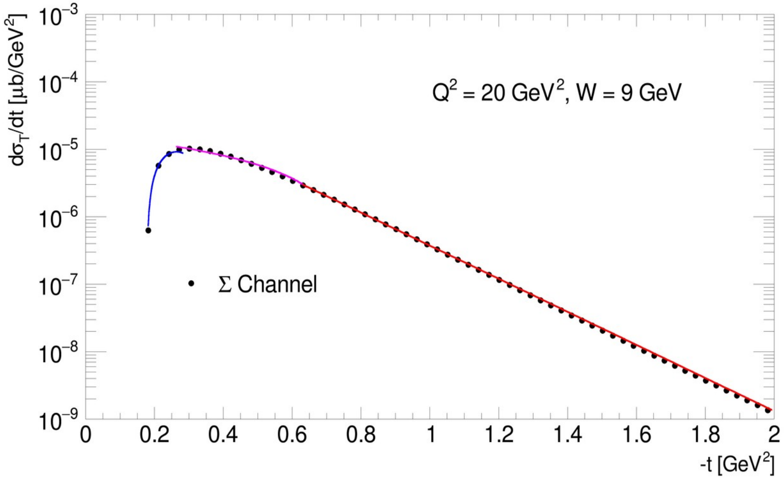

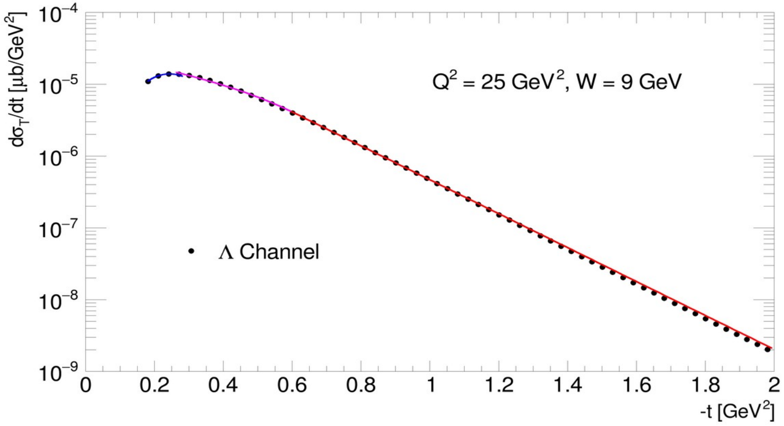

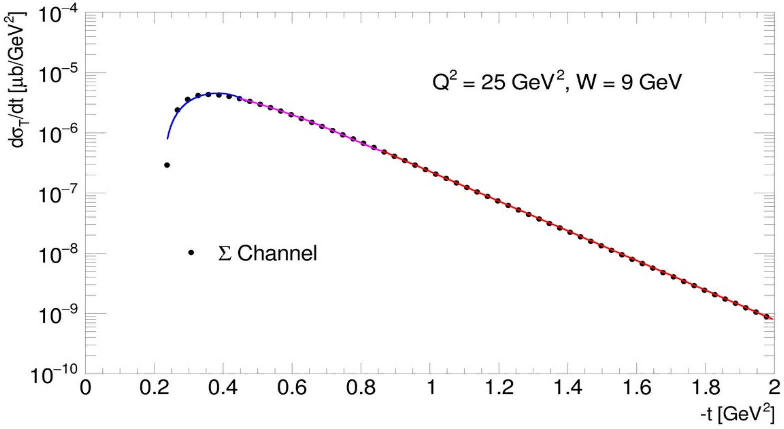

Summary

- New kaon DEMP event generation module for DEMPGen.
  - parametrized for Lambda and Sigma channels
- Implemented useful improvements to the generator.
  - Will incorporate them in the pion module too.
- Generator works and improvements made.
  - Will generate events and process them through the EIC ePIC simulation soon.
- Will give us an indication of the feasibility of kaon DEMP measurements at EIC.
- If the measurement is possible, we can measure the form factor of mesons over the wide kinematic range at EIC.
  - Will give us an insight into the mass generation mechanism of hadrons.

Thank you !

Supervisors - G. M. Huber, S. J. D. Kay

Meson Structure Working Group - **Stephen JD Kay**, **Garth M Huber**, Zafar Ahmed, **Love Preet**, **Ali Usman**, John Arrington, Carlos Ayerbe Gayoso, Daniele Binosi, Lei Chang, Markus Diefenthaler, Rolf Ent, Tobias Frederico, Yulia Furletova, Timothy Hobbs, Tanja Horn, Thia Keppel, Wenliang Li, Huey-Wen Lin, Rachel Montgomery, Ian L. Pegg, Paul Reimer, David Richards, Craig Roberts, Dmitry Romanov, Jorge Segovia, Arun Tadepalli, RichardTrotta, Rik Yoshida

EIC-Canada

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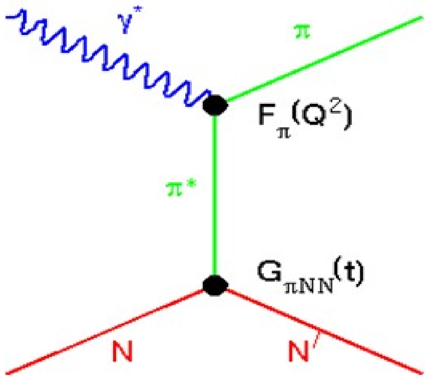
BACKUP SLIDES

Form Factor measurements

- At low four momentum transfer squared, Q^2, form factor can be measured directly through electron-pion elastic scattering.
  - CERN SPS used a beam of 300 GeV pions to measure the form factor up to $Q^2 = 0.28$ GeV^2.
  - Can't access high Q^2 as the stable pion targets are not possible (lifetime ~26 ns).
  - For $Q^2 = 1$ GeV^2 requires 1000 GeV pion beam!

- At larger Q^2, form factor can be measured through exclusive electro-production reactions.
  - Indirectly use the "pion cloud" of the proton via the $p(e,e'\pi^+)n$ process.
  - F_π can be linked to the cross-section, $_L$, by Born term model

$$\frac{d\sigma_L}{dt} \propto \frac{-t\,Q^2}{(t-m_\pi^2)}\, g^2_{\pi NN}(t)\, F^2_\pi(Q^2, t)$$



- Similar reaction for kaon.

Form Factor measurements at the EIC

- The produced hyperons (Λ^0 / Σ^0) are very forward focused.
- Carries majority of the momentum of the initial proton beam.
- Consider the Λ^0 channel, It will decay through two modes

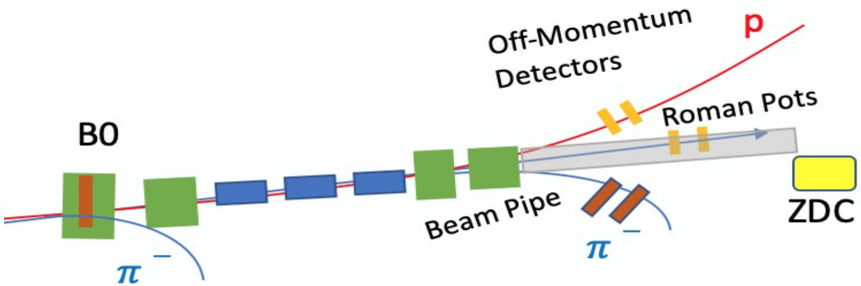
$$\Lambda^0 \rightarrow p\pi^- \sim 64\%$$

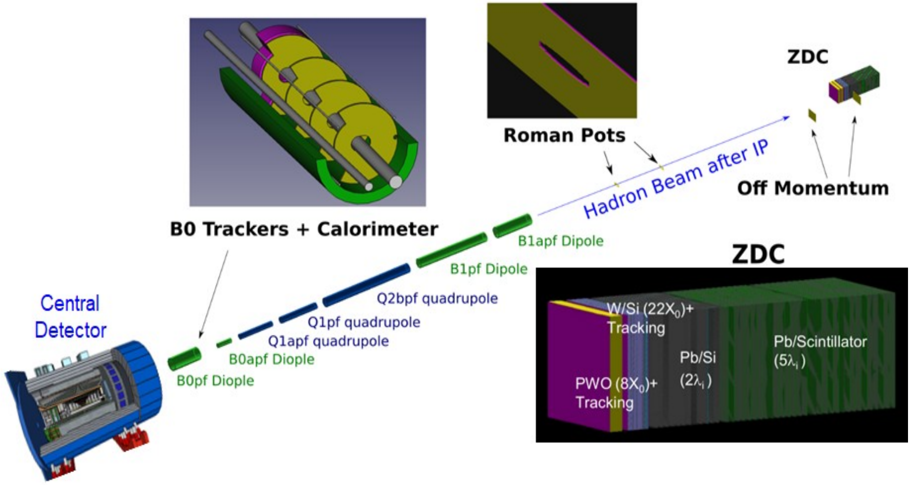
$$\Lambda^0 \rightarrow n\pi^0 \sim 36\% \quad (\pi^0 \rightarrow \gamma\gamma)$$

  - Neutral channel potentially good option.

- For Σ^0 channel, we have

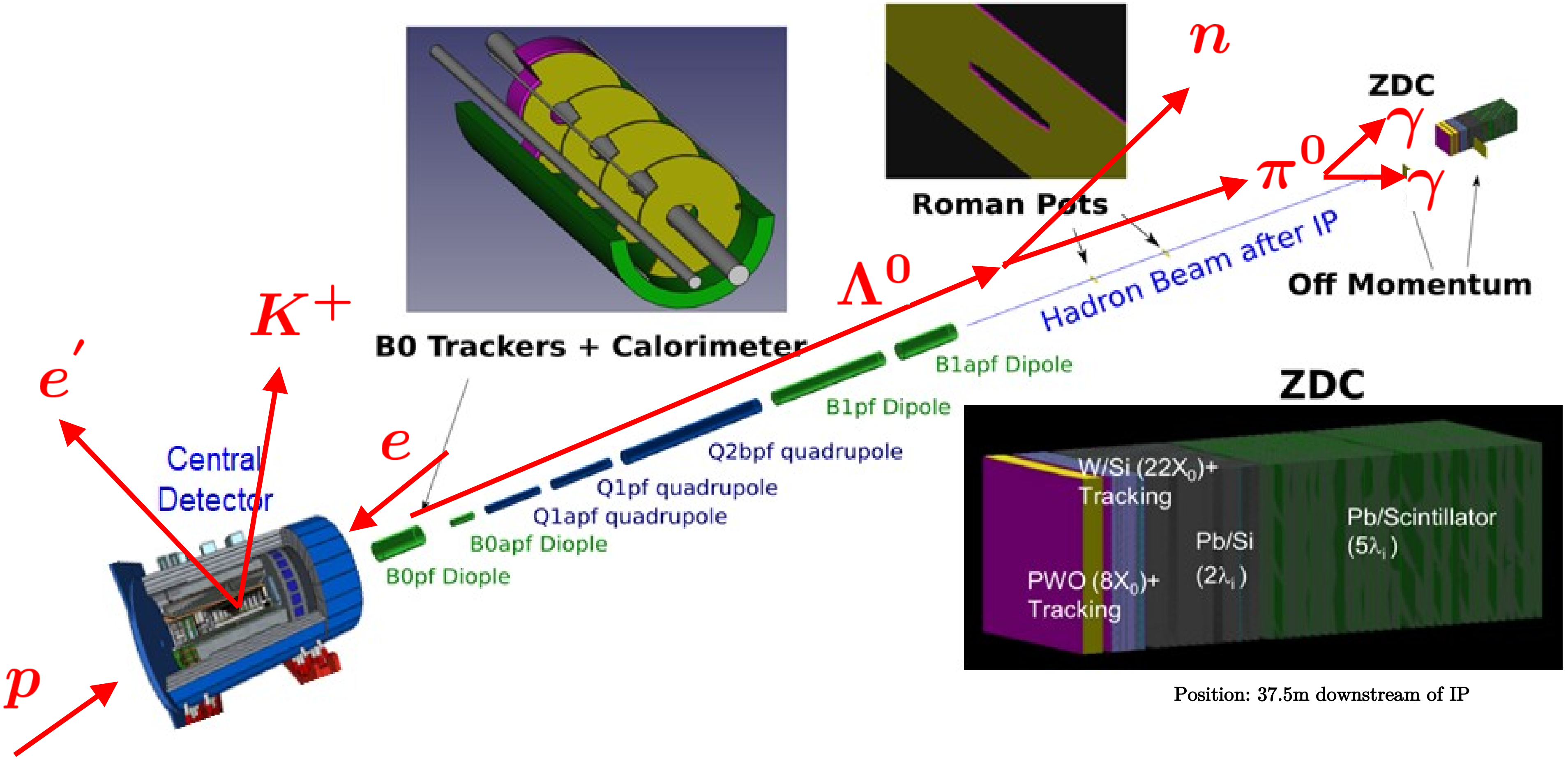
$$\Sigma^0 \rightarrow \Lambda^0\gamma$$





Position: 37.5m downstream of IP

Exclusive reaction



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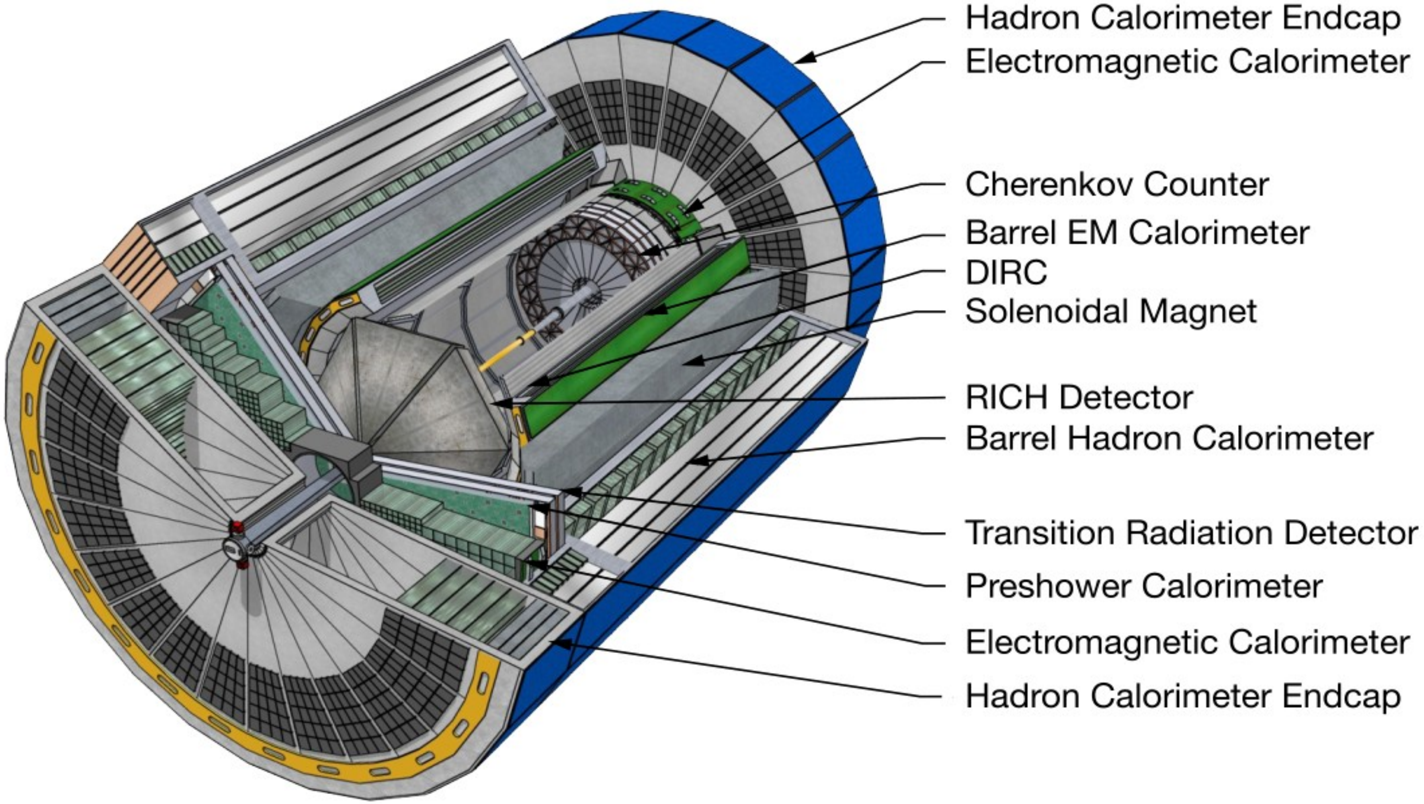
Detector Components



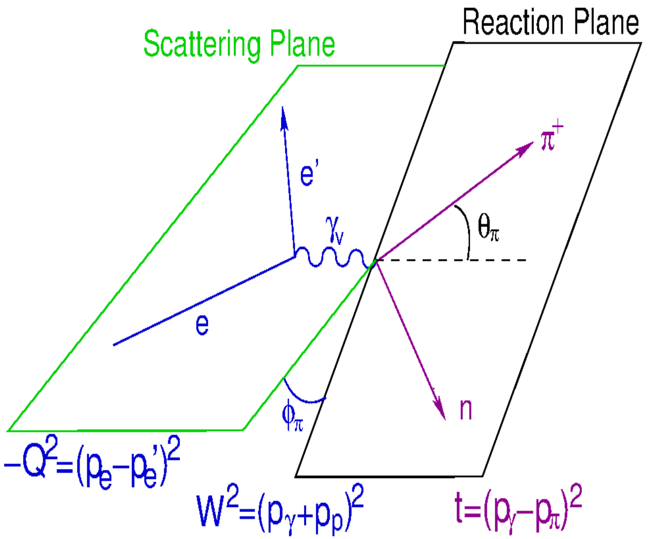
Total Cross-section Equation

- Total Cross section calculation,

$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\,\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt}\cos 2\phi$$

Virtual-photon polarization:

$$\varepsilon = \left(1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2}\tan^2\frac{\theta_{e'}}{2}\right)^{-1}$$



- Systematic uncertainties in σ_L are magnified by $1/\Delta\varepsilon$.

Event Weight in DEMPGen

- Assign weight to the events

$$Weight = \frac{\sigma \times PSF \times CF \times L}{N_{Gen}}$$

Where,

σ is the 5-fold differential cross section in the collider frame.

PSF is the phase space factor.

CF is a conversion factor to convert μb to cm^2.

L is the luminosity and

N_{Gen} is the number of events the generator tried to produce.

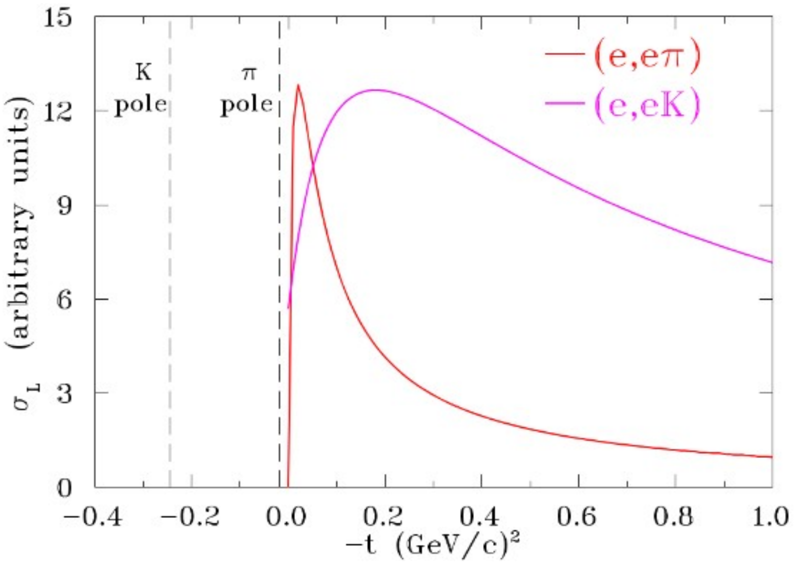
DEMPGen

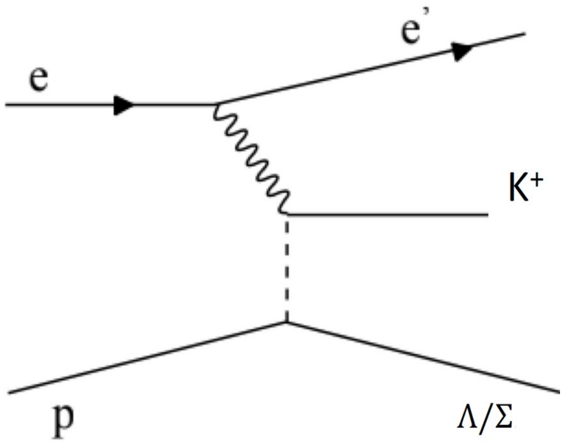
- Initial conditions
  - Beam energies for incoming particles.
  - Q^2 , W, -t values
  - Scattering Angles
  - Luminosity etc.

Why two channels?

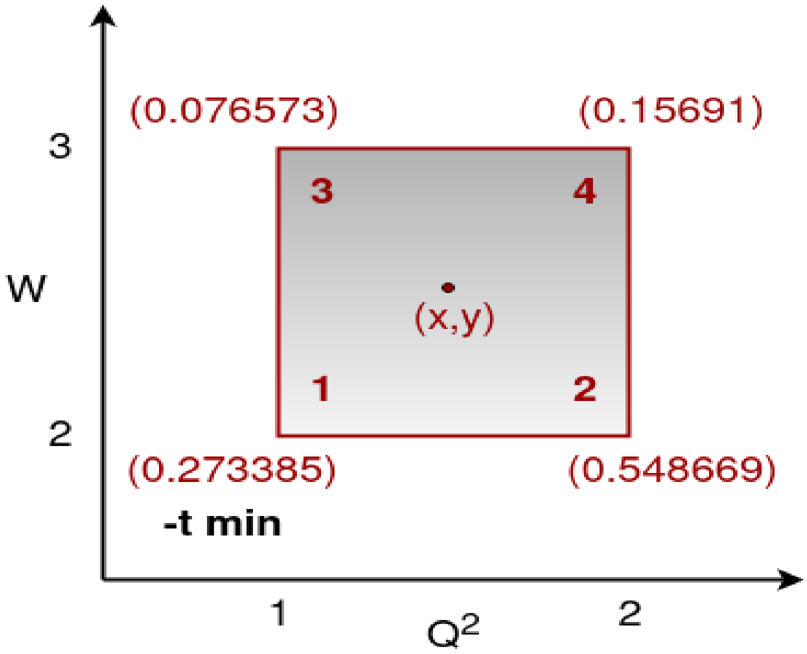
- Need both the channels for the pole dominance test

$$R = \frac{\sigma_L(e,e'K^+\Sigma^0)}{\sigma_L(e,e'K^+\Lambda^0)} \rightarrow R \approx \frac{g^2_{\rho K\Sigma^0}}{g^2_{\rho K\Lambda^0}}$$





Interpolation



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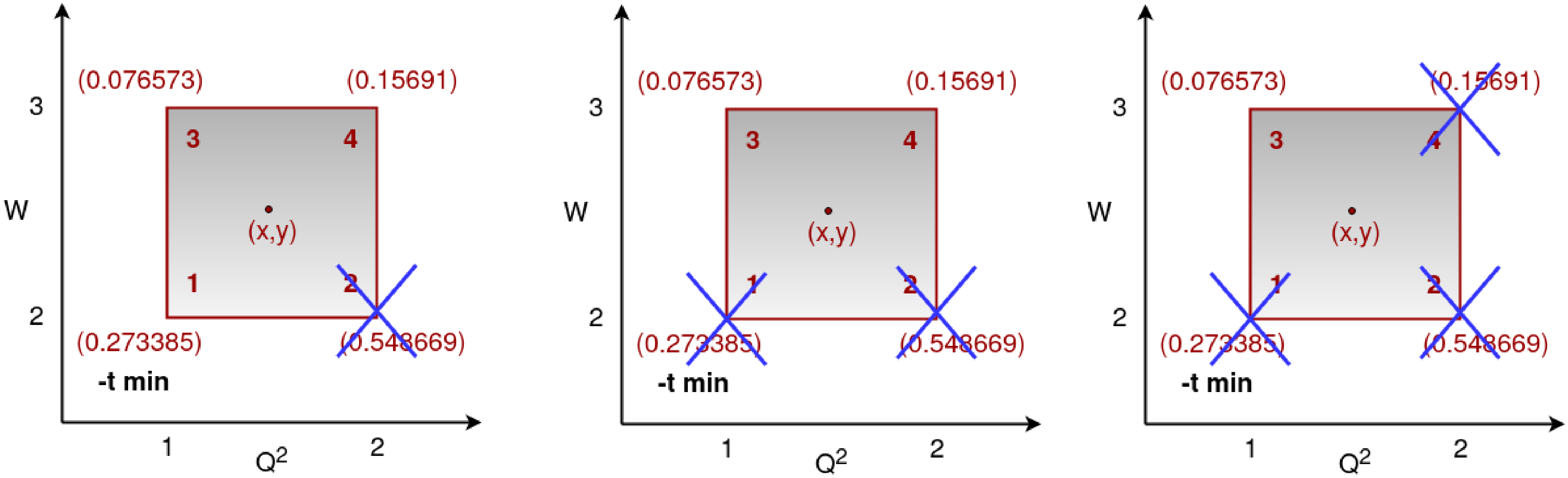


Find the value of either σ_T or σ_L at -t min point.
Then do interpolation with that value.

VGL Regge Model

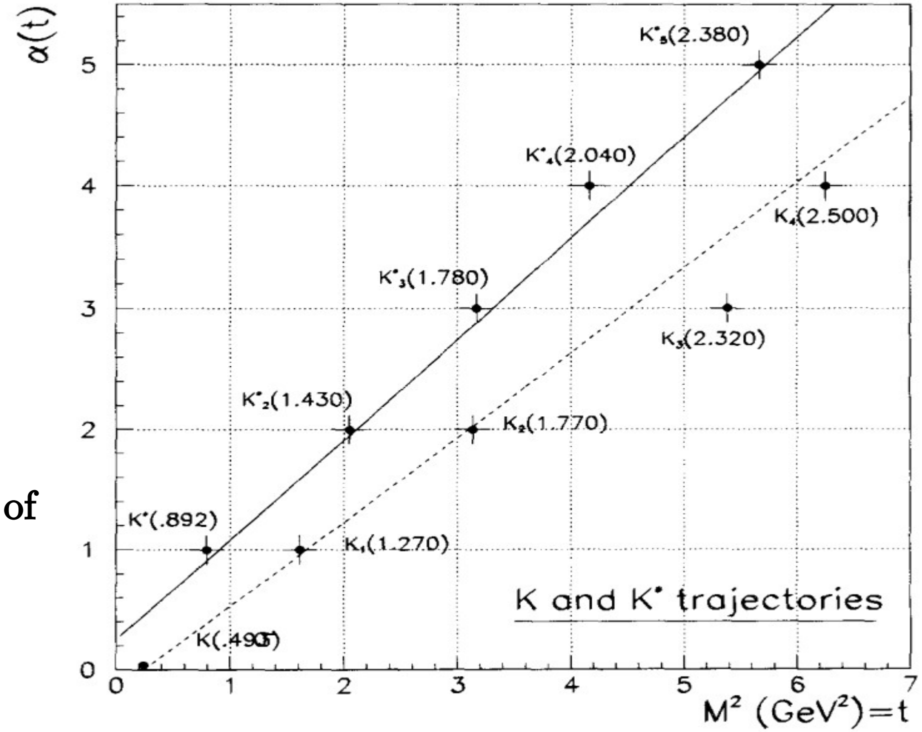
- Feynman propagator of a single particle i.e.

$$\frac{1}{(t - m^2)}$$

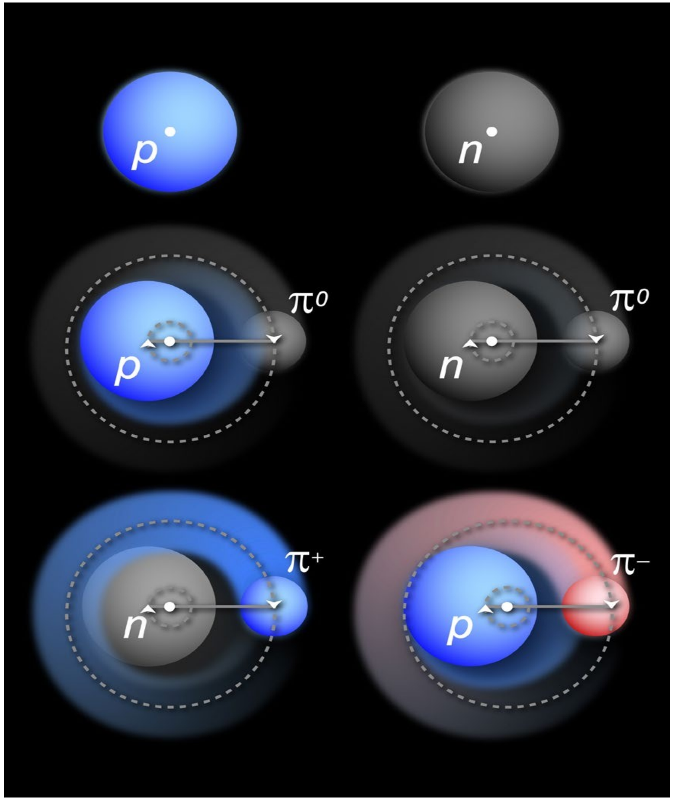
  Where m is the mass of the exchange particle.

- Replaced Feynman propagator by a so called Regge propagator.

- Regge trajectory represents the exchange of a family of particles with same internal quantum numbers.



Pion Cloud



- Electron beam is incident on the virtual meson cloud within a proton.
- Virtual photon interacts with the off shell pion (virtual), knocking it on shell (mass shell) and a recoil particle is produced.